

Flight Testing of an Airport Surface Guidance, Navigation, and Control System

Steven D. Young and Denise R. Jones
NASA Langley Research Center, Hampton, VA

BIOGRAPHY

Mr. Young and Ms. Jones have been working for the National Aeronautics and Space Administration since 1983 at the Langley Research Center in Hampton, Virginia. Since 1993, as a senior systems engineer and a project manager, respectively, in the Flight Electronics Technology Division, they have led a team of researchers who have been investigating the use of advanced technology to improve the safety and efficiency of airport surface operations. The research has been focused on low visibility and night-time operations at the major airport facilities. This work has included both flight simulation and flight test experiments.

ABSTRACT

This document describes operations associated with a set of flight experiments and demonstrations using a Boeing-757-200 (B-757) research aircraft as part of low visibility landing and surface operations (LVLASO) research activities. To support this experiment, the B-757 performed flight and taxi operations at the Hartsfield-Atlanta International Airport (ATL) in Atlanta, GA. The B-757 was equipped with experimental displays that were designed to provide flight crews with sufficient information to enable safe, expedient surface operations in any weather condition down to a runway visual range (RVR) of 300 feet. In addition to flight deck displays and supporting equipment onboard the B-757, there was also a ground-based component of the system that provided for ground controller inputs and surveillance of airport surface movements. The integrated ground and airborne components resulted in a system that has the potential to significantly improve the safety and efficiency of airport surface movements particularly as weather conditions deteriorate. Several advanced technologies were employed to show the validity of the operational concept at a major airport facility, to validate flight simulation findings, and to assess each of the individual technologies' performance in an airport environment. Results show that while the

maturity of some of the technologies does not permit immediate implementation, the operational concept is valid and the performance is more than adequate in many areas.

1.0 INTRODUCTION

In general, the LVLASO research is aimed at investigating technology as a means to improve the safety and efficiency of aircraft movements on the surface during the operational phases of roll-out, turn-off, inbound taxi, and outbound taxi. This investigation becomes critical in the face of growing demands for air travel, the increasing number of reported surface incidents (287 in 1996) and fatal accidents (five since 1990), and the economic, environmental, and geographic infeasibility of constructing new airports and/or runways. The goal of this research, which began in 1993, is to investigate technology as a means of making better use of existing runways and ideally, enable safe VMC capacities (i.e. flow rates) on the surface in weather conditions down to a visibility of 300'.

Specifically, the objectives of this flight test were (1) to demonstrate a prototype system that has the potential to meet the LVLASO goal, (2) to validate selected simulation findings and the operational concept at a major airport facility, and (3) to assess the performance and suitability of the prototype as compared to the operational requirements of an Advanced Surface Movement Guidance and Control System (A-SMGCS) [1], as well as the requirements of NASA's conceptual system.

The architecture defined for the prototype LVLASO system tested at ATL was derived from three constraints: do not add workload to the users of the system (i.e. pilots and controllers); focus on the needs of the users in IMC conditions, or at night, where hazardous situations are more likely and movements tend to slow down; and finally, make every effort to use technologies that are

either already part of the National Airspace System (NAS) or are planned to be in the NAS.

In order to operate safely in poor weather conditions at rates equal to those accomplished in clear weather, both pilots and controllers must be provided with information about the state of the airport environment. Assuming a fully operational aircraft, there are primarily three types of information required by the pilot to safely control the movement of the aircraft while avoiding an accident/incident on the airport surface. These are (1) continuous awareness of position, (2) continuous awareness of traffic or obstacle positions that may impede progressing to the destination, and (3) an understanding of the path to follow from current position to the desired destination. In the airport environment, controllers have similar needs when handling traffic on the surface, except they need to know (1), (2), and (3) for all vehicles. Controllers also have the responsibility of providing the route to all the vehicles/aircraft on the surface movement area.

Currently, position awareness on the surface is determined by both pilots and controllers by way of visual scans of the outside scene and, to a lesser degree, radio communications to confirm position. In most cases, painted centerlines and markings, airfield lights, and signage provide adequate information to crews to safely determine position. Occasional reference to a paper chart may also be done to get a "global" awareness of position, particularly at unfamiliar airports. Traffic and obstacles are also picked up via visual scan of the outside scene. The Traffic Alerting and Collision Avoidance (TCAS) system [2], which provides traffic information to pilots while airborne, is not currently used on the surface. The Airport Surface Detection Equipment (ASDE-3) radar is available at some airports and provides controllers with surface traffic positions on a radar screen. However, flight crews are not provided with this radar information. In addition, current ASDE-3 radars do not identify or track aircraft and can report "false" targets. Finally, the path to follow, or route, is provided via a voice channel to the crew by the air traffic controller, usually a specific "ground controller". The ground controller must maintain a mental picture of the routes given to all aircraft to avoid directing them into an unsafe position on the surface. Meanwhile, the crew must either memorize this path or write it down then follow the signage to the destination ramp or runway. Routes are read-back over the radio by the pilot as a means of confirmation.

Based on the significant dependence on visual scans, the ability to maintain situational awareness as the visibility drops, or even at night, becomes difficult because of growing uncertainties of position, obstacles/traffic, and even the path. This is especially true at unfamiliar airports. These uncertainties can cause pilots to slow down until the uncertainty is reduced to a comfortable level, or cause them to continue at the same speed but with reduced confidence and safety margin. Also,

dependence on voice communication as a sole source of route information can be unsafe due to the possibility of miscommunication or misunderstanding on the part of the pilot or the controller.

The system flight tested in Atlanta is an attempt to show how technology can be used in the near term to reduce the uncertainties mentioned above for both controllers and pilots. As will be shown, these uncertainties are reduced by providing them with supplemental guidance and situational information. This information is provided in a natural manner such that it reinforces any cues that are available and replaces those that are not available.

The system is based on several pieces of prior and related work. It is primarily based on "lessons-learned" in flight simulation studies both at NASA-LaRC [3], and at NASA-ARC [4]; a flight test performed at the FAA Technical Center in 1995 [5]; and two draft requirements documents [1] [6]. ICAO has sponsored the development of operational requirements for A-SMGCS [1] to describe a modular system consisting of several functions supporting safe, expeditious movement of aircraft and vehicles on the airport surface in all visibility conditions. Because the goals of A-SMGCS and the LVLASO research are so closely related, references to the A-SMGCS requirements will be made frequently in this document. The reader is encouraged to obtain a copy of [1].

2.0 SYSTEM DESCRIPTION

The system flight tested at ATL can be decomposed into surveillance, guidance, control, and routing functions as has been done for A-SMGCS. Also, it can be decomposed into the airborne and ground subsystems. Finally, it can be decomposed by operational phase (e.g. landing, roll-out, turn-off, taxi). Each of these decompositions will be referred to in this paper to describe the LVLASO system.

Physically, the prototype surface operations system consisted of both ground and flight components that were integrated via three digital datalinks as well as the normal voice channels. The flight system provided the flight crew with enhanced guidance and situational awareness information through the use of a head-up display (HUD) and a liquid-crystal display (LCD) which were added to the flight deck of the B-757. These displays were integrated with onboard sensors and datalinks that provided the necessary input data to the displays as well as providing aircraft state data to the ground components. The displays were designed to function based on the phase of flight. During high-speed roll-out and runway exit, the Roll-Out Turn-Off (ROTO) display symbologies and functions were engaged [7]. During taxi, the Taxi Navigation and Situational Awareness (T-NASA) display symbologies and functions were engaged [4]. Regardless of the phase of flight, the information presented on the displays was intended to supplement missing visual cues in low visibility situations or at night, and to reinforce

any available visual cues that may have an uncertainty associated with them (e.g. sign directional arrows, traffic positions, path to follow, etc.).

Similarly, ground-based components of the system provided the controller with supplemental information about traffic (e.g. position, identity, and intent), as well as a means for communicating with the flight crew over a digital link, in parallel with the normal voice channel. As with the flight crew, the information provided is meant to supplement missing visual cues and to reinforce uncertainties associated with whatever visual cues are available.

Functionally, the surveillance function is implemented on the ground (as described in 2.2), with its outputs being provided to the guidance, control, and routing functions. The guidance function provides advisory information to the vehicle/aircraft operator with inputs from the other functions. Control and routing functions are performed on the ground. Figure 1 shows how these functions relate and the data exchanged between them using the ATL architecture as a basis.

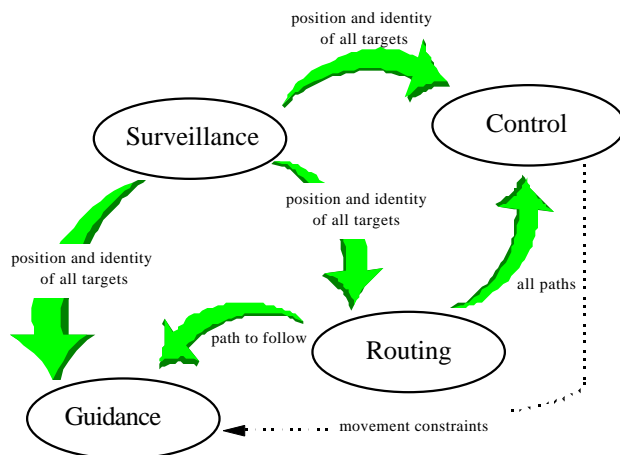


Figure 1. System Functional Decomposition.

From [1], surveillance is defined as a function that captures identification and positional information on aircraft, vehicles, and objects within a specific area. Control is defined as a function that applies measures for preventing collisions, runway incursions, and ensuring safe, expeditious, and efficient movement. Routing is defined as the planning and assignment of a route to individual aircraft and vehicles to allow safe, expeditious and efficient movement from its current position to its intended position. Finally, guidance is defined as necessary advisory information provided in a continuous unambiguous reliable manner such that pilots and/or vehicle operators can steer their aircraft or vehicle along the assigned route while maintaining an appropriate velocity.

2.1 FLIGHT SYSTEM

As mentioned previously, the ATL testing was conducted using a B-757 research aircraft. Modifications to the flight deck included installation of three hardware devices (figure 2).



Figure 2. B-757 Flight Deck.

A HUD device was mounted to be used from the left seat position. The HUD consisted of a projector, mounted above and behind the pilot, and a combiner glass mounted between the pilot's eyepoint and the front left windscreen. This specific HUD was manufactured by Flight Dynamics, Inc. and was capable of projecting a holographic image onto the combiner based on a raster-type graphics input. The field of view was 30 degrees horizontal by 24 degrees vertical. The HUD was used to support the guidance function of the experimental system as described in 2.3.

An active matrix LCD device was mounted under the glare shield and was used to render the moving map symbologies described in 2.3. This LCD was manufactured by Rockwell-Collins. The LCD was sunlight readable and provided 1024x768 pixel resolution. The viewing area was 8"x6" and had a 65 degree horizontal viewing angle which allowed for viewing by both crew members.

A Pilot Input Device (PID) was mounted on the center aisle stand. The PID allowed the pilots to control the experimental displays. The controls are described in 2.3.

Aft of the flight deck, pallet workstations contained the necessary on-board systems required for data recording, power, datalink, and display generation. Figure 3 depicts the experimental flight system.

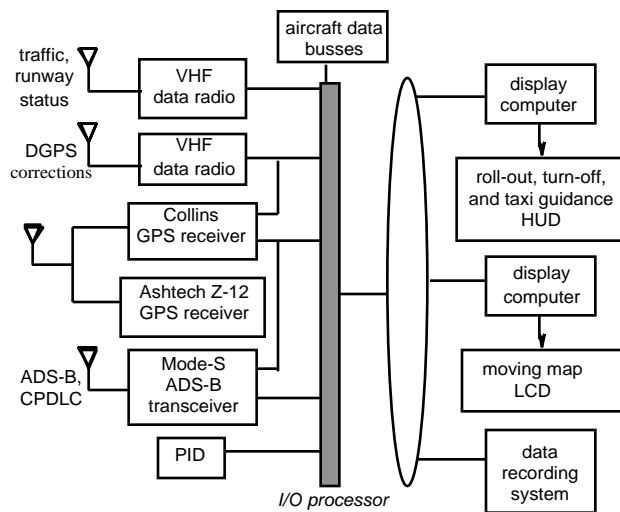


Figure 3. Experimental Flight System.

Two VHF data radios and their supporting antennas were provided by Rockwell-Collins and were set to operate in receive mode only. The first of the two was responsible for receiving DGPS corrections and forwarding them to the GPS receiver. The second radio was responsible for receiving traffic and runway status information provided by the ground-based surveillance system. This data was then forwarded to the I/O processor for eventual display on the LCD as described in 2.3. The radios employed the Differentially encoded 8-Phase Key Shifting (D8PSK) modulation waveform and adhered the RTCA standard protocol DO-217 [8].

A modified Mode-S transceiver broadcast GPS position reports, also known as Automatic Dependent Surveillance Broadcast (ADS-B), to the ground-based surveillance system as well as supporting the bi-directional Controller-Pilot Datalink Communications (CPDLC). CPDLC format adhered to the RTCA standard protocol DO-219 [9]. CPDLC messages were forwarded to the I/O processor for eventual display as described in 2.3.

The I/O processor was responsible for reformatting data received by the experimental datalinks and providing it to the display computers. This processor also relayed data to be downlinked to the test controller at the ground site via the Mode-S transceiver. Finally, the unit integrated DGPS and IRU position data and provided it to the display computers. Blending of DGPS and IRU position data was critical to ensure a continuous position update on the two experimental displays and to minimize the variance of the position reports. Without a blending function, the displays would “jump” at a 1 Hz rate and be distracting to the pilots. Also, this blending allowed for intermittent outages of the DGPS system.

As described in [10], the GPS position data from the Collins’ GPS receiver was input into the I/O processor and passed through a complementary filter to produce GPS derived position. This filter was initialized to IRU

velocity and acceleration values. Once the filter is initialized, each input of GPS data is saved and propagated forward using the velocity estimates. Each subsequent input is compared to the propagated value of the previous input, and rejected if it differs by more than a preset limit. If the data is valid and passes this limit test, it is differenced with the saved value of the filter position output corresponding to the age of the current GPS position. The difference vector is then input to the complementary filter to correct the position estimate. This resulting position estimate is that of the CG of the aircraft. With GPS data valid, Differential GPS available (DGPS) and acceptable HDOP and VDOP, the filter is checked for convergence. Once the average length of the difference vector has converged, a flag is set and the display system is permitted to use the derived position estimate. This flag remains set so long as valid data continues to be received. If this flag was not set, the experimental displays would alert the pilot(s) that the position report is not valid. This was done by flashing the text “DGPS INVALID” on both displays.

An independent GPS system was employed using an Ashtech Z-12 receiver. This system recorded GPS data and, along with data stored at the ground site (see 2.2), allowed for post-processing that resulted in nominal 5cm accurate position data [11]. This data was used to evaluate the accuracy of the experimental real-time position determining system described above. The two GPS receivers on the aircraft shared the same antenna.

2.2 GROUND-BASED SYSTEM

The ground-based subsystem, illustrated in figure 4, included the surveillance, control, and routing functions. It also enabled the transfer of required information among the ground components and to/from the B-757 via datalink. Equipment was located at two sites at ATL: the control tower, and atop the Renaissance Hotel just north of the movement area.

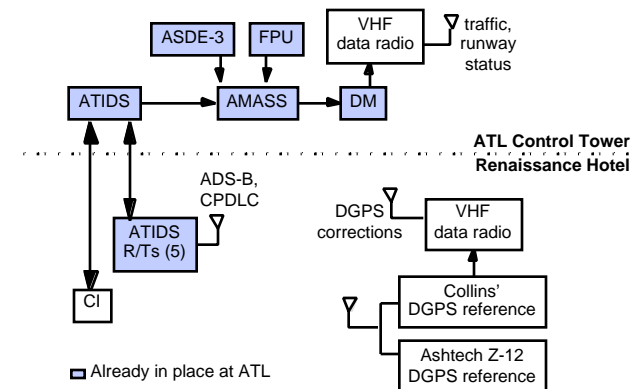


Figure 4. Experimental Ground-Based System.

The surveillance system development was led by the Federal Aviation Administration (FAA) and consisted of four primary elements that were integrated in an attempt

to provide full coverage of the airport surface, to provide identity information to both pilots and controllers, and to collect data so that multipath mitigation algorithms can be developed. Requirements for a surveillance function are listed in [1]. The elements of the surveillance function used for the ATL testing were:

The Airport Surface Detection Equipment (ASDE-3) captured position data (range and azimuth) for all aircraft or vehicles operating on the airport surface movement area at a one hertz rate. ASDE-3 is a radar operating in the Ku-band (15.7 - 16.2 GHz). ASDE-3 does not require any equipment on aircraft or vehicles and is capable of detecting targets with a cross section as small as three meters. Its range is specified to be 24,000 feet in all directions on the surface and up to 200' above the surface. ASDE-3 and its associated display is scheduled for deployment at 40 airports over the next four years. Although ASDE-3 is a high performance radar system, it does have certain limitations. ASDE-3 has a 500' "cone-of-silence" area encircling the antenna. Targets in this area are not visible by ASDE-3. In fact, at ATL, taxiway Dixie passes through this cone of silence (figure 5). Aircraft taxiing on Dixie disappear from the ASDE-3 display while in this cone of silence. Further, there can be other coverage gaps with particular ASDE-3 installations as it is a line-of-sight radar. For example, at ATL, the section of Echo running parallel to RWY 26L on the east end of the airport is not covered by ASDE-3 because of a "FLY DELTA" sign. Because of this issue, siting of the ASDE-3 is critical to ensure maximum coverage. Also, ASDE-3 is susceptible to multi-path reports. Energy pulses emanating from the radar can return after reflecting off several mediums along its path. This can result in a false target being reported and possibly displayed. Finally, ASDE-3 does not report target identity information. It is because of these three issues (coverage, multi-path, and identification), that the other surveillance systems described below were integrated with ASDE-3 for this testing to hopefully ensure full coverage, minimal multi-paths, and identification which are required in [1].

The Airport Surface Target Identification System (ATIDS) captured position and identity data for aircraft and ground vehicles equipped with ADS-B and/or Mode-S transponders. At ATL, ATIDS utilized five fixed receiver/transmitters (R/Ts) located on the north side of the airport (figure 5). These R/Ts performed a multilateration function [12] on targets emanating a Mode-S beacon. The result of this multilateration function was the position and identity of any equipped target with its Mode-S transponder operating. In addition, ATIDS captured the ADS-B transmissions emanating from the B-757 at any or all of its five R/T sites. ADS-B transmissions include position and identity information [13]. All position and identity data captured by ATIDS, in addition to data it acquired from the FPU (described below), was forwarded to the AMASS computer (described below) for "fusion" with the data from the other surveillance sensors. The ATIDS update

rate was specified to be one hertz. The coverage area for the ATL ATIDS was specified to be only on the north side of ATL out to 500' beyond the approach end of the runways and up to 500' above the surface.

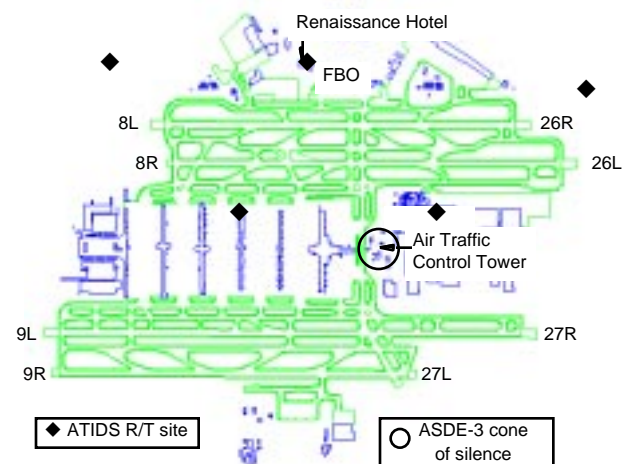


Figure 5. ATL Airport Layout.

The Airport Movement Area Safety System (AMASS) provided the following: (a) tracking of ASDE-3 targets; (b) data fusion of ATIDS target data (captured via multilateration or ADS-B) with ASDE-3 track data, and (c) safety logic to detect runway incursions and alert controllers and the test pilots. AMASS has been designed to visually and aurally prompt controllers to respond to situations which potentially compromise safety. AMASS was also responsible for passing target information and runway status to a datalink manager (DM) for forwarding to the B-757. Runway status information consisted of hold lines drawn along the runway edge lines at locations where taxiways intersect the runway. These lines turned red (on both the controller and cockpit display) when high speed runway traffic (either landing or taking off) was approaching a specific intersection. These red lines turned off after the aircraft/vehicle passed the intersection. By knowing the runway status, pilots are less likely to enter the runway at an unsafe time.

A Flight Plan Unit (FPU) provided a transparent interface to the ARTS-IIIA system database. This allowed ATIDS to extract the Mode-A code, the aircraft call sign, and the aircraft type from the database, in real-time, and associate this information with specific Mode-S transmissions received. All retrieved information was forwarded to AMASS for use by the fusion function.

This resulting fused surveillance data was provided to and displayed on both the test ground controller display (described below) and the B-757's experimental LCD. This enabled both the pilots of the B-757 and the controller to have the same "picture" of the airport surface traffic at any point in time. This is a requirement specified in [1].

Supporting the guidance function (as well as the ADS-B portion of the surveillance function) of the system, a GPS ground station was implemented to provide differential corrections. This ground station operated independently of all other systems. It consisted of two GPS receivers and a VHF data radio. These three components were identical to those used onboard the research aircraft. One of the two GPS receivers was an Ashtech Z-12 that was responsible for storing data that could be used subsequent to the flights to obtain high accuracy truth data. The other was the Rockwell-Collins GPS receiver that operated in conjunction with the D8PSK radio transmitter to fully implement the RTCA DO-217 specification [8].

The DM was responsible for converting surveillance system data received from AMASS into the protocol required by the D8PSK transmitter. The DM was designed to be able to support multiple transmitter types simultaneously such that aircraft/vehicles with different receivers could acquire the traffic broadcast. This enables alternate datalinks to be utilized.

Supporting the routing and control functions of the system, a Controller Interface (CI) allowed a test controller to mimic normal voice instructions in parallel, and then transmit these instructions digitally for display in the flight deck of the B-757. The CI is described in more detail in 2.3.3.

2.3 DISPLAY SYMBOLOGIES

2.3.1 MOVING MAP LCD

The experimental LCD onboard the B-757 provided both crewmembers with:

- depiction of the airport layout;
- depiction of current position/heading of the B-757;
- depiction of current position of other traffic;
- display of ATC instructions including the taxi route;
- display of runway status.

See figure 6 for a depiction of the LCD map symbologies used at ATL. This format is part of the Taxiway Navigation and Situational Awareness (T-NASA) system that has undergone human factors testing in several simulation studies [4][14][15]. In addition to the input data received from the datalinks and the DGPS/IRU system onboard, an accurate airport database was also required. This database was provided by Jeppesen-Sanderson and included all runway/taxiway edges and centerlines as well as hold-short lines. These were all required to be accurate to one foot.

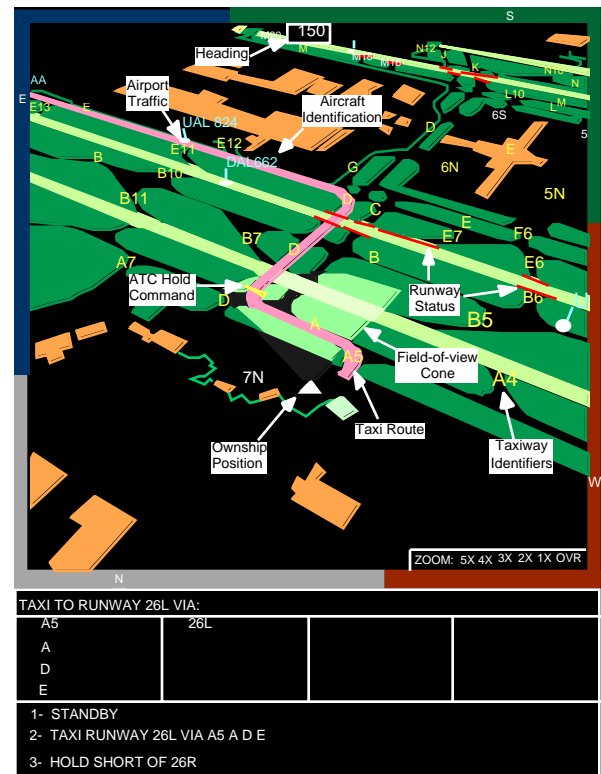


Figure 6. ATL Map LCD Symbologies.

Using the PID, the flight crew was able to select from six zoom levels, one of which was an overview of the airport. The airport overview zoom level was north up while all other zoom levels were track up. The crew also had the choice to display symbols for other traffic and, if traffic was displayed, show traffic identification labels, if desired. The capability also existed to scroll through the list of ATC instructions displayed in the bottom portion of the map LCD.

In addition to rendering the display, the map computer generated downlink messages that were relayed to the test controller at the ground site. For example, if the B-757 deviated from the route issued by ATC, a message was sent to the test controller alerting him of this deviation. Similarly, if the B-757 returned to its approved path, a "taxi route resolved" message was sent to the test controller.

Along with the normal activities associated with operating the aircraft on the surface, the map LCD symbologies supported the guidance function of the system and was provided to remove guidance/navigation uncertainties that can become substantial in lower visibilities and at night. The display does this primarily by increasing the crew's situational awareness.

2.3.2 ROLL-OUT, TURN-OFF, AND TAXI GUIDANCE HUD

On the HUD, from final approach until the B-757 had safely exited the runway, the roll-out and turn-off (ROTO) symbologies were enabled. Specifically, while in the landing phase, the ROTO system displayed symbology similar to the symbology found on commercial HUD systems designed to provide landing guidance. During the final approach, the pilot selected an exit using the PID. The exit chosen was displayed on the HUD in a box in the upper right-hand portion of the display. Along with the exit chosen, the box also listed the desired exit speed and the estimated distance from the projected touchdown point to the exit. Once the aircraft landed and the nose strut was compressed, the symbology transitioned from the in-flight symbology to the roll-out and turn-off guidance symbology (figure 7). While rolling out, the symbologies presented attempt to reinforce visual cues that may be difficult to see (i.e. runway edges and runway remaining markers) as well as provide a deceleration profile to follow that will minimize runway occupancy time to the chosen exit. In particular, the velocity error bar on the left wing of the velocity vector symbol and the projected exit speed listed on the left tells the pilot, at any point in time, whether he is moving too fast or too slow to make the exit at the desired speed. By following the profile and adjusting his speed as he approaches the exit, the pilot will be able to take the exit at the desired speed. Again, these symbols are provided so that the pilot can maintain or reduce VMC roll-out turn-off times in IMC conditions or at night.

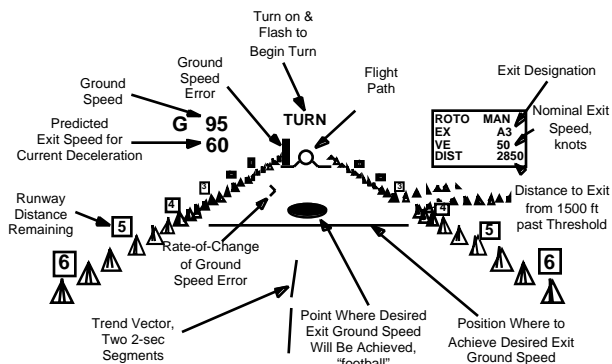


Figure 7. Roll-out Turn-off HUD Symbols.

As the taxi route was delivered by the test controller after exiting the runway, the symbology transitioned from the ROTO mode to the taxi mode. The taxi symbols are shown in figure 8.

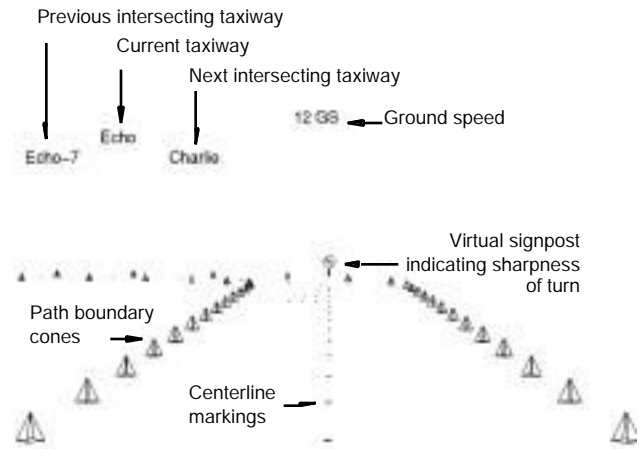


Figure 8. Taxi HUD Symbology.

All HUD symbols were displayed relative to the pilot's eye reference point such that they overlaid the outside scene (e.g. the painted centerline stripe). The taxi HUD display format is part of the T-NASA system that has undergone human factors testing in several simulation studies [4][14][15].

Along with the normal activities associated with operating the aircraft on the surface, the HUD symbologies supported the guidance function of the system and was provided to remove guidance/navigation uncertainties that can become substantial in lower visibilities and at night.

2.3.3 CONTROLLER INTERFACE

During the testing, a ground controller located at a test site had access to a controller interface (CI) in addition to his normal visual scans and voice communications. The CI provided:

- electronic flight strips updated in real-time;
- continuous display of surface traffic positions and identification on an airport map;
- controller instruction capture and datalink to the B-757 via voice recognition or touchscreen;
- alerts of route deviation by the B-757;
- runway exit taken by the B-757.

See [16] for a detailed description of the CI.

3.0 FLIGHT TEST OPERATIONS

The deployment to ATL occurred in two separate sessions, July 31 to August 8, and August 18 to August 29, 1997. The first session included end-to-end operational checks of all systems. Also, during this session, all flight tests using NASA test pilots as subjects were completed. The second session consisted of flight tests (using commercial B-757 captains as subjects) and demonstrations for visitors from the aviation community.

Because the CI was at the prototype stage, a test controller was used. This controller was located at the ground site (not in the tower cab) and monitored ATL ATC communications. Any verbal instructions designated for the B-757 were sent electronically, in parallel, to the aircraft via datalink and the voice recognition function of the CI. These were then displayed on the two experimental flight deck displays as described in 2.3.

The crew were instructed to utilize the HUD and map LCD, while maneuvering the B-757, on an as-needed basis. The HUD was to be used by the captain for supplemental guidance cues and enhanced situational awareness. The map LCD was to be used primarily by the first officer for situational awareness which could then be relayed to the captain if necessary. The captain could refer to the map LCD if desired. During test runs, the flight crew could manipulate the map LCD using the PID as desired (scroll through ATC messages, display traffic and labels, and change the field of view). Specific details on how to use the LVLASO display system were provided as part of each pilots' training procedure prior to the flight experiment.

3.1 FLIGHT TEST PROCEDURE

All flight test runs began in the ramp area located at the Fixed Base Operator (FBO) just north of runway 8L/26R (see figure 5). At start, the responsible flight deck crew member called for taxi instructions from ATL ATC. Once ATC verbally relayed the taxi instructions to the B-757, the test controller repeated those instructions verbally into the voice recognition system and they were sent electronically to the B-757 for display on the experimental displays. The captain then taxied to the designated departure runway. After taking the runway, the B-757 would either (1) takeoff/circle/land or (2) taxi down the runway depending on the test run. Once clear of the runway, the B-757 verbally received a taxi instruction from ATC. Again, this taxi instruction was sent to the B-757 by the test controller in parallel. After the crew acknowledged receipt of the instruction, the captain taxied back to the FBO ramp area following the designated path. While taxiing, the captain was instructed to taxi at a normal taxi rate or higher if he felt safety was not being compromised.

If a specific run included a landing, an ILS autoland was used to minimize the touchdown dispersion. On approach, the captain would choose the exit using the PID. After touchdown and the nose strut was compressed, the captain disengaged the autopilot and manually performed the roll-out and turnoff procedure following the ROTO guidance symbology on the HUD. If a takeoff was not required for a specific test run, the B-757 taxied down the runway and exited as directed by ATC. The ROTO system was not part of these runs. These runs were performed to evaluate only the taxi guidance system onboard (T-NASA).

3.2 TEST MATRIX

Tests were defined to fulfill the goals of the testing while staying within the constraints placed on the deployment in terms of time and operational costs. The test variables were: time of day (day/night), HUD state (on/off), LCD state (on/off), left-seat captain, landing required or taxi-only, exit chosen, and southside or northside operation. Tests runs were done predominantly at night as this more closely represents a "low visibility" condition. A total of 53 test runs were successfully completed which resulted in 1378 minutes of audio, video, and digital data. The average run time was 26 minutes.

4.0 RESULTS

While the primary objective of this effort was to demonstrate the feasibility of the operational concept at a major airport facility, secondary objectives were to obtain data to (1) validate simulation findings and the operational concept, and (2) assess the performance of the individual technologies and the system as a whole. Meeting these objectives has been done using both qualitative (subjective) data and quantitative recorded digital data.

4.1 RECORDED DATA

During the testing, data was taken in several formats. Test pilots and demonstration visitors completed questionnaires to obtain their expert, albeit subjective, opinion of the system as implemented in Atlanta. Also, audio/video recordings of all camera images and the experimental displays were made of each test run. This allowed for review of specific events, either noted while reviewing the questionnaire responses, or, while reviewing the recorded digital data. Finally, digital data was recorded onboard the B-757 and on five systems on the ground: the CI, AMASS, ATIDS, the DM, and the DGPS ground station. All digital data was timestamped using the GPS time reference.

4.2 QUALITATIVE RESULTS

Validating the feasibility of the system concept has been accomplished, in part, by obtaining qualitative questionnaire data and comments from test pilots during data collection runs and visitors from the aviation community during the demonstration runs. Comments were also obtained from air traffic controllers that viewed the ATL testing. 87 of the 110 attendees completed a brief questionnaire. The vast majority of the visitors either agreed or strongly agreed that these technologies would help enhance both capacity and safety on the airport surface. A detailed analysis of the subjective data will be published in a separate report. Finally, it should be noted that simply operating the system (including the B-757) through this series of tests in the environment of a busy international airport facility and not negatively impacting

normal operations substantiates the operational concept to some degree.

4.3 QUANTITATIVE RESULTS

In order to assess the system performance as well as the performance of individual technologies, metrics have been defined which can be quantified using recorded data. Assessment of the prototype system includes evaluation of each major subsystem:

- flight deck displays
- datalinks
- onboard position determination system
- surveillance system
- controller interface

4.3.1 FLIGHT DECK DISPLAY PERFORMANCE

A large part of the assessment of the flight deck displays involves assessment of the effectiveness of the man-machine interface during the testing. This analysis is being done by our partners at NASA-Ames Research Center and will be reported in a separate document. However, display performance can also be characterized by the update rates and the latencies associated with the symbologies being presented to the crew. Failure rates of displays are also important, however, for this testing, there were no failures of the display system. This does not imply that the displays had a failure rate of zero, simply that they did not fail over the relatively short period of testing in Atlanta. For example, the advertised failure rate of the HUD was 8000 hours, while the total duration of all flight tests at ATL was just over 23 hours.

With the exception of the taxi route (which was displayed as it arrived), all HUD symbologies were updated at 10-15 hertz depending on the amount of symbologies being presented at any point in time during the flight. B-757 position and heading information presented on the map LCD were updated at 25 hertz. Traffic and runway status data were updated at one hertz. Controller instructions arriving via the CPDLC datalink for display on the map LCD were updated as they arrived.

Latency is the delay associated with processing information. The only significant latency observed was that associated with the traffic data. The ground-based surveillance system could take as long as one second to "scan" the airfield for traffic before it forwarded the entire scan of data to the B-757. Onboard, the I/O processor waited until it had received a full scan of traffic before it forwarded it to the display system. This took up to one additional second if traffic conditions were heavy and the datalink became loaded. Thus, the latency for the display of traffic data on the map LCD varied between one and two seconds depending on the number of targets on the airport surface. For the largest number of targets that occurred during the testing (47), the latency was ~2 seconds. Alternate means of data processing could improve this latency (e.g. draw every target report as it is

received). Latencies for drawing all other symbologies were near zero (i.e. not measurable).

4.3.2 DATALINK SYSTEM PERFORMANCE

Datalink performance can be quantified using several metrics. These include coverage, signal strength, and availability. Coverage is defined here to be the surface area over which the datalink performed correctly (as specified). Signal strength is the amount of signal detected at the receiver at a specific range from the transmitter. Availability will be defined as the fraction of time that the datalink was operating correctly (as specified) during any given time interval.

The four datalinks utilized at ATL were the VHF datalink for DGPS corrections, the VHF datalink for traffic data, the CPDLC datalink, and the ADS-B datalink.

VHF Datalink Performance

Datalink performance was characterized for the VHF datalinks onboard the B-757 by recording DGPS position and datalink message status outputs from the GPS receiver; and also by recording received signal strength outputs based on internal receiver Automatic Gain Control (AGC) information from the VHF DGPS datalink receiver. Three states of message status were recorded: (1) no message received, (2) message received but CRC failed, and (3) message received and CRC passed successfully indicating a correctly received message. Because the two VHF datalink applications (corrections and traffic) utilized identical hardware and an identical protocol (DO-217), an independent evaluation of the traffic datalink will not be presented here. The only difference was the specific application data placed in the messages.

Coverage was excellent on the airport surface as well as in the pattern out to about 10 nmi. Signal strengths ranged from -67 to -77 dBm in this area which is also very good. During flights to/from ATL, the range was observed to be ~70 nmi. During flights R062 through R066, the total number of messages transmitted was 42204. Of these, 42115 were correctly received (99.79%). 68 of 42204 were garbled (0.16%) and 21 of 42204 were not received at all (0.05%). Only once was there a three second outage and only three times was there a two second outage. All other outages were one second in duration.

The effective bandwidth utilized for the VHF datalinks can also be quantified. Because the traffic datalink requires the most bandwidth and is dependent on current traffic conditions, it can have the most impact on system performance. For these tests, the maximum number of targets seen by the surveillance system at any time was 47. This translated to 6256 bits of data to be transmitted in one second using the message format defined for these tests. This represents only 20% of the specified 31500 bits per second budget. The DGPS corrections messages used less than one third of one of the eight TDMA slots

as per DO-217 [8] and ARINC 743A [17]. Only 112 + 48n bits per second (where n is the number of satellites) of the 31500 bits per second bandwidth budget were utilized for DGPS corrections. Even for 12 satellites, this is only 688 bits per second.

CPDLC Datalink Performance

Because controller-pilot datalink messages were very short and infrequent, the primary metric of interest is the percentage of messages that were lost in transmission. For the entire testing period, 97% (516/534) of the CPDLC downlink messages (e.g. “Roger”) from the B-757 were correctly received by the test controller. 92% (432/470) of the CPDLC uplink messages (e.g. “Taxi to RWY 8L via Alpha”) sent by the test controller to the B-757 were correctly received. This is very good performance considering the fact that two modems had to be used to transfer messages to/from the two ground sites prior to transmission to/from the B-757 over the Mode-S link.

ADS-B Datalink Performance

This specific issue is of paramount importance to the aviation community as the current NAS plans suggest possible world-wide equipage with ADS-B capability in the future [13]. As with any new technology with such a scope, there are a multitude of metrics that must be quantified to ensure safe robust use in the NAS. Examples are coverage, capacity, update rate, and transmission waveform and frequency. With only one ADS-B participant for these tests at ATL, most of these issues could not be addressed. However, Rannoch Corporation has been tasked with assessing the ADS-B performance observed at ATL. This will be published in a separate report. One metric that has been quantified is the error-free ADS-B reception percentage. Table 1 shows the ADS-B reception percentages for four representative flight days at ATL along with the overall performance.

Table 1. Error-free ADS-B Reception.

Flight#	EFSR	EXSR	%
R055	3278	3343	98.1
R056	8330	8539	97.6
R057	6276	6438	97.5
R058	4630	4778	96.9
Overall	51050	52870	96.6

EXSR is the expected squitters to be received (i.e. two per second) and EFSR is the error-free squitters received by at least one of the five ground-based R/Ts at ATL.

4.3.3 ON-BOARD POSITION DETERMINATION PERFORMANCE

Determining the position of the B-757 onboard and in real-time was accomplished using inputs from the DGPS system and the Inertial Reference Unit (IRU) as described in 2.1. Several metrics can be defined related to the accuracy of the position reports. These include the root-mean-square (RMS) error, the cross track error, and the along track error. In addition, horizontal and vertical dilution of precision (HDOP and VDOP) values are produced by the GPS receiver. These metrics are summarized in table 2. Only surface data is used and as such the RMS error is only calculated for the horizontal plane (i.e. altitude errors are not included). Finally, a valid DGPS solution was produced and available for 41379 of the 41715 seconds considered when generating table 2. This constituted 99.2% availability for this time interval.

Table 2. DGPS Performance.

Metric	Mean	StDev
RMS (m)	0.78	0.52
Cross track (m)	-0.04	0.60
Along track (m)	0.07	0.72
HDOP	1.51	0.19
VDOP	-2.20	0.34

It is important to note that the real-time position observed by the flight crew on the experimental displays (both the HUD and the LCD) was derived from the raw DGPS sensor data (presented in table 2) and data coming from the IRU. The result of this “blending” function was a robust, continuous update (25 Hz) that removed much of the “noisy” behavior of the raw DGPS updates. The DGPS/IRU solution converged to the mean error while at the same time minimized the variance of the error over time. It is recommended that some form of DGPS/IRU blending (like the one implemented at ATL) be performed, if possible, to avoid erratic unreliable updates of position being presented to pilots on a guidance/navigation display. This implementation was also able to tolerate intermittent outages of DGPS while still converging to the an accurate position. A detailed analysis of the DGPS/IRU data as compared to just DGPS data will be published in a separate report.

All test pilots commented favorably on both the tracking of the position updates on the displays with the visual scene, and the alignment (on the HUD) of projected symbols with physical guidance cues (e.g. painted centerlines). This is due to the DGPS/IRU blending function performance and the accuracy of the airport database.

4.3.4 SURVEILLANCE SYSTEM PERFORMANCE

The majority of the surveillance data recorded at ATL will be analyzed and documented in a separate report being prepared by the FAA. This includes data from the

three surveillance sensors employed (ASDE-3, ATIDS multilateration, and ADS-B) as well as the sensor fusion results. Several metrics are being quantified including dropouts (and where they occurred), multi-path reports (and where they occurred), accuracy (of the three surveillance sensors individually and of the fused result), latency, and capacity.

4.3.5 CONTROLLER INTERFACE SYSTEM PERFORMANCE

Performance of the CI is documented in [16]. The primary metric of interest is the success rate of the voice recognition component. For the entire duration of the testing at ATL, the probability of correctly recognizing a verbal instruction was 89.1% (490/550). However, during the final 12 test runs, the probability was 99.2% (123/124). During these runs, it was decided to limit the vocabulary of the system to one unique to the ATL airport layout. For example, the system was trained to recognize only the eight runway names used at ATL instead of any runway name. Using this constraint significantly improved performance. It should be noted that training of the voice system took approximately 20 minutes for a given individual.

5.0 CONCLUSIONS

This activity has demonstrated the potential for using technology and a holistic systems approach for improving the safety and efficiency of airport surface operations. By providing supplemental guidance and situational awareness information to both pilots and controllers, safety margins can increase as there is more confidence in the understanding of the current state of the airport surface. In poor visibility, at night, or at unfamiliar airports, this supplemental information becomes critical, particularly if VFR flow rates are expected to be maintained safely. Although this system was not demonstrated in low visibility, the questionnaire responses received from the test subjects and the visitors from the aviation community clearly support this conclusion. In addition, many of the proposed operational requirements for A-SMGCS [1] were demonstrated.

This activity also revealed that there can be a near-term implementation of many of the demonstrated technologies. ASDE-3 and AMASS are already part of the NAS providing surface surveillance information to controllers. DGPS has been standardized for Special Category I (SCAT-I) landings [8] and is the primary sensor for the planned Wide-Area Augmentation System (WAAS) and Local Area Augmentation System (LAAS). HUDs exist onboard many commercial jets providing takeoff and landing guidance to flight crews. In fact, the unit used onboard the B-757 for these trials was manufactured for commercial use onboard a Saab 2000 aircraft. Finally, thousands of Mode-S transponders, similar to the one used in this test, are currently onboard commercial aircraft.

A secondary goal of this activity was to validate the operational concept. As described earlier, this concept is to provide pilots with (1) continuous awareness of position on the airport surface, (2) continuous awareness of aircraft/obstacle positions, and (3) continuous awareness of path/route to follow from current position to the destination. The concept provides the controller with position reports for all vehicles operating on the airport surface, a secondary link with flight crews, and awareness of any route deviations. This operational system concept was demonstrated and shown to be valid at ATL. This implementation augmented available visual cues and assumed a ground-based surveillance system at the airport, an accurate position sensor onboard, and a ground-based route generation method. It should be noted, that specific technologies are not being advocated, but were merely used as a means to validate the concept. Specific technologies were evaluated and may be recommended in the future.

In order for this operational concept to meet its full potential, there are technical challenges that still must be overcome (e.g. multi-path mitigation, robust voice recognition, moving map retrofit, software certification, crew roles and procedures, and guidance-to-the-gate). These will be addressed as the research continues. Partial implementations of this system can be implemented in the near-term to provide many benefits with only minimal additional technical work. In terms of operations, the intent is to design a system that has minimal impact on normal operations and procedures. The aids are provided to pilots and controllers in such a way as to not increase workload and to be used only as needed to supplement, or reinforce visual cues.

The research program deliverable is a set of operational and technical requirements for a system that safely enables VMC capacities at airports in IMC conditions down to Category III-B. Through this flight test activity, a significant step has been taken toward providing that deliverable to the aviation community.

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